Cosmic-ray experiment EMMA: Tracking analysis of the first muon events

T. Räihä*, T. Enqvist*, J. Joutsenvaara*, J. Karjalainen*, P. Kuusiniemi*, K. Loo*, L. Olanterä*, J. Sarkamo*, E. Heikkilä†, P. Jones†, T. Kalliokoski†, K. Kolos†, W.H. Trzaska†‖, H. Fynbo‡, L. Bezrukov§, L. Inzhechik§, B. Lubsandorzhiev§, V. Petkov§

**CUPP, University of Oulu, Finland*
†*University of Jyväskylä, Finland*
‖*Helsinki Institute of Physics, Finland*
‡*University of Århus, Denmark*
§*Russian Academy of Science, Moscow, Russia*

***Abstract*. The cosmic-ray experiment EMMA is designed to measure the multiplicity and lateral distribution of high-energy muons. It is placed at the depth of 80 metres (∼225 mwe) in the Pyhäsalmi mine. Four detector stations have been built and the new gas control system is ready. The position and efficiency calibration of drift chambers have been started in the surface laboratory in Pyhäsalmi. Calibrated detectors will be first installed into the three-layer station C. Muon angular and multiplicity distributions can be already deduced from measurements of station C and, after the full-size array is ready, the study of the composition of cosmic rays around the knee energy may start.**

***Keywords*: high-energy muons, composition, knee energy**

I. INTRODUCTION

The observed cosmic-ray energy spectrum steepens slightly at energy 3×10^{15} eV which is called the knee region. Its origin is often linked to supernova remnants that are generally assumed to be the main source of high-energy cosmic rays. Since the supernova remnants are considered to accelerate light particles only up to approximately 3×10^{15} eV, they would result in a decrease of the cosmic-ray flux above the knee. If the origin of the knee is explained by supernova remnants, it would indicate a transition in the average cosmic-ray composition from lighter to heavier particles around the knee.

Due to a low flux the high-energy cosmic rays can only be studied indirectly by measuring secondary particles produced in cosmic-ray induced extensive air showers (EAS). Several experiments have been built to investigate the composition of cosmic rays around the knee region. They are based, for instance, on the measurement of the shower maximum by Cherenkov or fluorescence light, on the multi-component analysis of EAS, on the measurement of the Cherenkov light profile of muon bundles under the ice, or on the muon multiplicity measurements underground. So far the results diverse implying the need for new approaches to study the primary composition.

EMMA (Experiment with MultiMuon Array) [1] is a new approach since, in addition to multiplicity, it can measure the lateral distribution of high-energy muons (E > 40 GeV) under the ground. The shape of the lateral distribution profile of high-energy muons is sensitive to the mass and the multiplicity in the shower centre is sensitive to the energy of the primary particle.

II. EMMA EXPERIMENT

The EMMA experiment is being built at the depth of 80 metres (∼ 225 mwe) in the Pyhäsalmi mine. The rock overburden filters out the hadronic and electromagnetic component of the EAS providing a minimum threshold energy of 40 GeV for vertical muons.

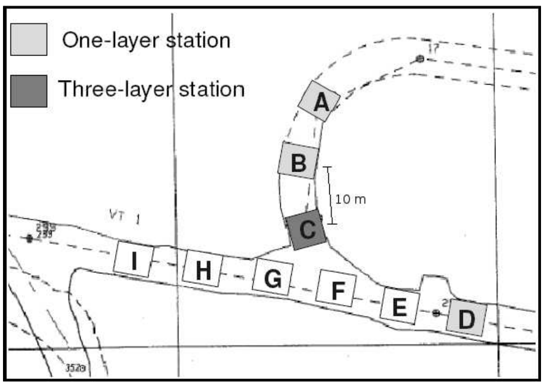

Fig. 1. A layout of EMMA. Structures of detector stations A-D have been constructed of which in the station C the detectors will be set in three layers.

EMMA will ultimately consist of nine detector stations (15 m^2 each) which will be constructed in the existing cavern with mutual distances of 10 metres as illustrated in Fig. 1. The stations form a three-arm structure, each arm extending up to 25 metres from the centre of the array. The stations are warmed inside and they protect detectors from humidity, dust and acid water which are common features in the mine environment.

Structures of four detector stations (stations A-D) are already constructed. Detectors in the stations will be set either in one or three layers. The effective detector surface area will be approximately 135 m^2 and the area, where events can be reconstructed properly, will be approximately 300–400 m^2.

The main part of EMMA is composed of drift chambers (MUBs) previously used in the LEP-DELPHI experiment [2]. Most of the drift chambers have a gas volume of $365\times20\times1.6$ cm^3. The drift chambers are operated with a non-flammable Ar:CO_2 (92:8) gas mixture, having a position resolution of a few centimetres. They are organised in groups of seven chambers, called detector planks, each plank covering the area of $\sim$3 m^2 (75 planks in total).

The planks will be placed into detector stations in one or three layers. In three-layer stations the tracks of muons can be reconstructed to obtain a shower direction and muon numbers. First, the calibrated detectors will be installed into three-layer station C (see Fig. 1).

The Russian Academy of Science will provide 1536 pieces of high-granularity plastic scintillation detectors ($12\times12\times3$ cm^3 each) covering the total area of 24 m^2. They will be mounted below the planks in three-layer stations to improve the track reconstruction of high-density muon bundles. First scintillation detectors have been tested in Pyhäsalmi, and the rest of the detectors will be delivered from Russia later this year.

The new gas control system was recently constructed for the EMMA experiment. Now the gas is mixed on the surface and blown into a gas line going from surface down to the EMMA site. Previously the gas bottles were transported to EMMA site which was time consuming and a safety risk.

III. Calibration of detectors

The efficiency and position calibration of detector planks have been started in the surface laboratory in Pyhäsalmi (see Fig. 2). The calibration setup consists of a stack of eight planks, of which four planks have been calibrated with a radioactive ^{22}Na source. The calibrated reference planks are then used to calibrate other four planks with atmospheric muons. The calibration of each four-plank set requires roughly three-weeks data taking after which they are ready to be delivered underground.

Preliminary results of the reconstructed muon angular distributions for the calibration data measured in the surface laboratory are presented in Fig. 3. In the analysis it was required that the muons have to pass through all eight planks which caused clear geometrical cuts in the distributions. Reconstructed hit positions were not calibrated yet. The results will be compared with predictions obtained from simulations later this year.

IV. Track reconstruction

High-energy muons of EAS are produced at high altitudes and they arrive on the ground almost parallel with the shower direction. Even after the passage through the rock to the EMMA site the high-energy muons have retained their original direction mostly with a one degree accuracy. The parallelism of high-energy muons can be used to reconstruct the shower direction and muon numbers.

Fig. 2. A calibration setup constructed of eight detector planks in the surface laboratory in Pyhäsalmi.

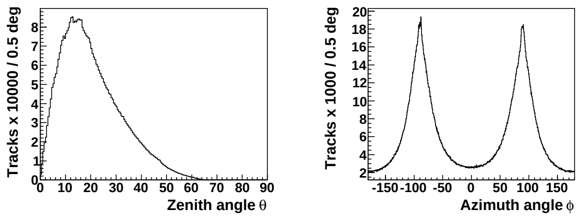

Fig. 3. Reconstructed angular distributions of muons measured with the calibration setup in the surface laboratory. The results are preliminary since reconstructed hit positions were not calibrated yet.

The tracks of muons can be reconstructed in detector stations where the planks are set in three layers. In each plank, the drift chambers are installed in two layers, and therefore one muon can produce hits in six chambers in maximum. In addition, the track reconstruction is improved if the muon passes through plastic scintillation detectors that will locate below the planks.

Muons tend to produce local electromagnetic showers in the rock from which some electrons may enter the EMMA cavern and produce hits in detectors. The detectors itself cannot identify electrons from muons but the tracks of electrons can be generally recognised by their relatively large deviations with respect to the shower direction. Despite of it the electrons are a small source of uncertainty in the analysis.

It is expected that EMMA is able to reconstruct also high muon densities using three-layer stations. Very high muon multiplicities were measured in cosmic-ray experiments at LEP (DELPHI [3], CosmoALEPH [4], and L3+C [5]) that were not expected from the basis

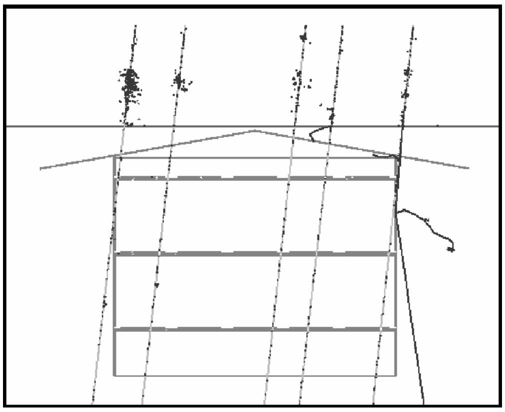

Fig. 4. Geant4 simulations: a bundle of five muons comes from the rock, enters the EMMA cavern, and traverses through the structures and detectors of a three-layer station.

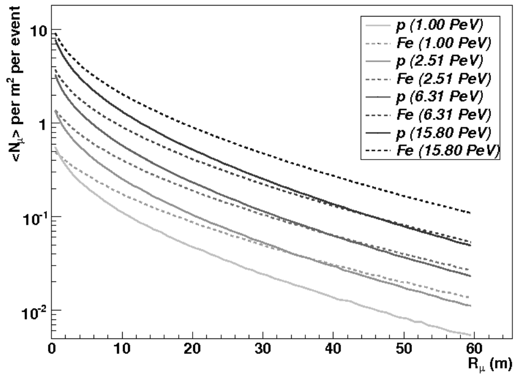

Fig. 5. Average lateral density distributions of high-energy muons of vertical proton and iron showers at different primary energies simulated with CORSIKA-QGSJET01. The threshold energy of muons was 50 GeV which corresponds roughly to the average energy loss of muons in rock.

of simulations. Such high-density events could be used to evaluate modern high-energy hadronic interaction models used in EAS simulations.

V. Data analysis

Data analysis is based on simulations in which the evolution of EAS is simulated with CORSIKA [6] and the traverse of high-energy muons ($E > 40$ GeV) through the rock to EMMA site with Geant4 [7]. Low-energy muons and other charged particles are absorbed in the rock and therefore they can be neglected in simulations. The effect of rock on the direction and energy of muons can be estimated because the composition of the rock overburden is known from several drilling samples performed by the mine company. The passage of muon bundles through the detector stations are simulated in detail with Geant4 as shown in Fig. 4. It illustrates a bundle of five muons entering the cavern from the rock and traversing through the structures and detectors of a three-layer station. The hit information of muons and muon-induced electrons can be recorded including the position resolution and efficiency of the detectors which then can be used later in data analysis.

The analysis of the average chemical composition of cosmic rays with the full EMMA array will be based on the dependence of the shapes of lateral muon density profiles on the primary mass. The lighter is the primary particle, the steeper is the average muon density profile. The primary energy is proportional to the muon density in the shower centre and is almost independent on the primary type (see Fig. 5).

The composition study will be based on a two-component analysis in which protons and iron nuclei represent the light and heavy component, respectively.

For the analysis a capability to locate the shower axis from the measured distribution of muons is of great importance. The axis and composition reconstruction is done by fitting a two-dimensional parameterised function to the hit distribution. By selecting only showers, whose axis will be reconstructed close to the centre of EMMA, the required accuracy will be achieved.

VI. Summary

The construction of the EMMA experiment is going well. Position and efficiency calibration of drift chambers are in progress and the analysis of the first muon measurements performed with the calibration setup are under the study. The calibrated detectors will be first placed into the three-layer station C. The muon angular and multiplicity distributions will be reconstructed from the first measurements and, after the construction of EMMA is completed, the study of the composition of cosmic rays may start.

References

[1] T. Enqvist *et al.*, *EMMA - a new underground cosmic-ray experiment*, Nuclear Physics B (Proc. Suppl.) (2008) 175-176.
[2] DELPHI Collaboration, Nuclear Instruments and Methods A303, (1991) 233.
[3] Petr Travnicek, *Detection of high-energy muons in cosmic-ray showers*, Charles University, Prague, 2003, PhD. Thesis.
[4] V. Avati *et al.*, Astroparticle Physics 19 (2003) 513.
[5] H.G.S. Wilkens, *Experimental study of high-energy muons from extensive air showers in the energy range 100 TeV to 10 PeV*, University of Nijmegen, 2003, PhD. Thesis.
[6] D. Heck *et al.*, Report Forschungzentrum Karlsruhe 6019 (1998).
[7] S. Agostinelli *et al.*, *Geant4 - a simulation toolkit*, Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303.